AFRL-RY-WP-TR-2017-0157

REVIEW OF RADIO FREQUENCY PHOTONICS BASICS

Preetpaul S. Devgan

RF/EO Subsystems Branch
Aerospace Components & Subsystems Division

SEPTEMBER 2017
Final Report

Approved for public release; distribution is unlimited.
See additional restrictions described on inside pages

STINFO COPY

AIR FORCE RESEARCH LABORATORY
SENSORS DIRECTORATE
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7320
AIR FORCE MATERIEL COMMAND
UNITED STATES AIR FORCE

NOTICE AND SIGNATURE PAGE

AFRL-RY-WP-TR-2017-0157 HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION IN ACCORDANCE WITH ASSIGNED DISTRIBUTION STATEMENT.

*//Signature//

PREETPAUL S. DEVGAN, Program manager
RF/EO Subsystems Branch
Aerospace Component & Subsystems Division

*//Signature//

TIMOTHY R. JOHNSON
Chief
RF/EO Subsystems Branch
Aerospace Component & Subsystems Division

*Disseminated copies will show "//Signature//" stamped or typed above the signature blocks.

REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
September 2017	Final	March 1, 2007 – July 31, 2017

4. TITLE AND SUBTITLE
REVIEW OF RADIO FREQUENCY PHOTONICS BASICS

5a. CONTRACT NUMBER
In-house

5b. GRANT NUMBER
N/A

5c. PROGRAM ELEMENT NUMBER
N/A

6. AUTHOR(S)
Preetpaul S. Devgan

5d. PROJECT NUMBER
N/A

5e. TASK NUMBER
N/A

5f. WORK UNIT NUMBER
N/A

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
RF/EO Subsystems Branch (RYDR)
Aerospace Components & Subsystems Division
Air Force Research Laboratory, Sensors Directorate
Wright-Patterson Air Force Base, OH 45433-7320
Air Force Materiel Command, United States Air Force

8. PERFORMING ORGANIZATION REPORT NUMBER
AFRL-RY-WP-TR-2017-0157

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory
Sensors Directorate
Wright-Patterson Air Force Base, OH 45433-7320
Air Force Materiel Command
United States Air Force

10. SPONSORING/MONITORING AGENCY ACRONYM(S)
AFRL/RYDR

11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)
AFRL-RY-WP-TR-2017-0157

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
The U.S. Government is joint author of the work and has the right to use, modify, reproduce, release, perform, display or disclose the work. PAO case number 88ABW-2017-4067, Clearance Date 23 August 2017. Report contains color.

14. ABSTRACT
Photonics can operate essentially from "Direct Current to Daylight," allowing use for high frequency applications. This report covers some needs and advantages of radio frequency (RF) photonics. Also a comparison of analog and digital metrics is covered. The findings show the analog delay line has an important purpose and is a good use for a RF photonic link. In addition, the external intensity modulation combined with direct detection link is the preferred option.

15. SUBJECT TERMS
radio frequency, photonics, compression dynamic range, spur free dynamic range

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT:	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON (Monitor)
Unclassified	Unclassified	Unclassified	SAR	21	Preetpaul S. Devgan
					19b. TELEPHONE NUMBER *(Include Area Code)* N/A

Table of Contents

Section **Page**

List of Figures

Figure **Page**

1. INTRODUCTION

Radio frequency (RF) photonics uses photonic components for signal processing of RF signals. This area is also called microwave photonics.

This field encompasses up-converting RF signals into the optical domain, performing some function and then down-converting the signal back to an electrical signal. Functions include transmitting a signal, filtering the signal and many others.

Photonics can operate essentially from "Direct Current (DC) to Daylight," allowing use for high frequency applications. The following sections of this report cover some needs and advantages of RF photonics. Also a comparison of analog and digital metrics is covered.

Figure 1 shows an example of an RF delay line using RF photonic technologies, including a laser, modulator, optical fiber and photodiode.

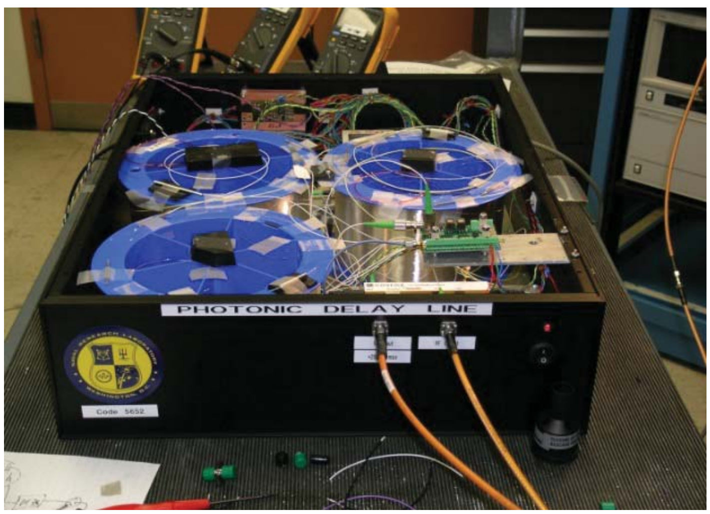


Figure 1: Example of RF Delay Line using RF Photonics

2. THE NEED FOR RF PHOTONICS

Wireless signals continue to take up the available frequency spectrum leaving higher frequencies open for new uses. Frequency bands from 600 MHz to 5 GHz are used for commercial communications in the US. The future will require higher frequencies for more data in wireless systems such as 5G. Figure 2 shows the loss in the atmosphere is very low (<1 dB/km) from 1 to 100 GHz. RF photonics can be used for future 5G technologies, as well as other wireless communications. RF photonic technologies can also be used in antenna remoting for radio astronomy.

Arrays of large dish antennas, which collect very faint radio waves from space, are spread out over multiple kilometer distances from each other. RF photonic links can connect the antennas. Other examples of antenna remoting exist including moving a base station from the antenna site by up to several kilometers.

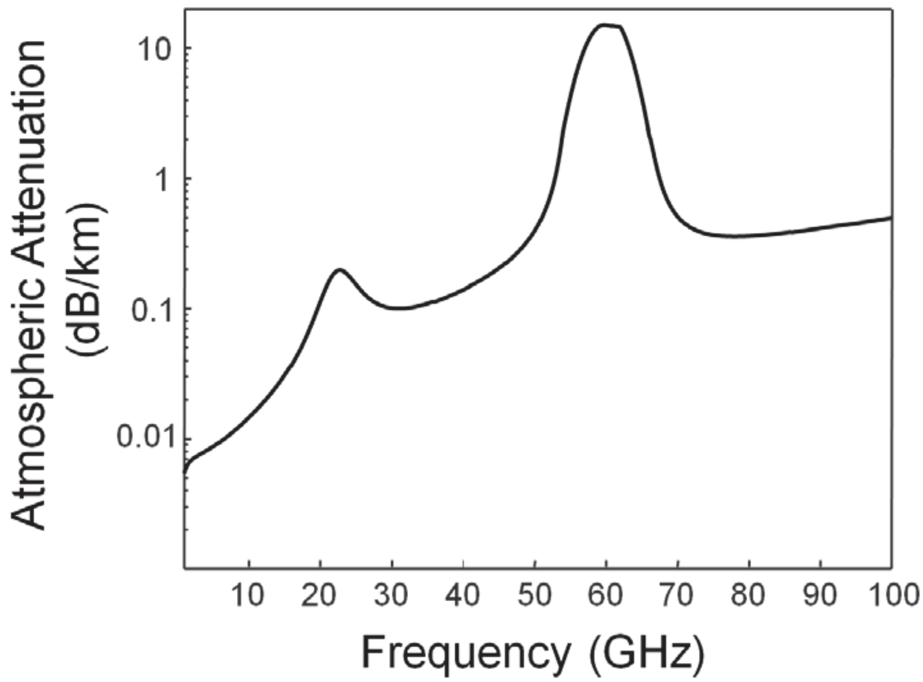


Figure 2: Loss in the Atmosphere from 1 to 100 GHz

3. RF PHOTONIC ADVANTAGES

RF photonics offers advantages in comparison to electronic equivalents. Comparing the transmission lines, photonics uses a single mode fiber optic cable. The single mode optical fiber has an inner core diameter of 9 microns and an outer cladding diameter of 125 microns. The electronic coaxial cable consists of a copper inner conductor copper, surrounded by an outer conductor. The size of the inner conductor depends on the frequencies that the cable is designed to transport. Fiber optic cables' losses approach the Rayleigh scattering limit. Figure 3 shows power loss of a fiber versus wavelength. The loss decreases as the wavelength increases. Minimum loss window centers at 1550 nm. Above 1600 nm, IR absorption dominates losses increase.

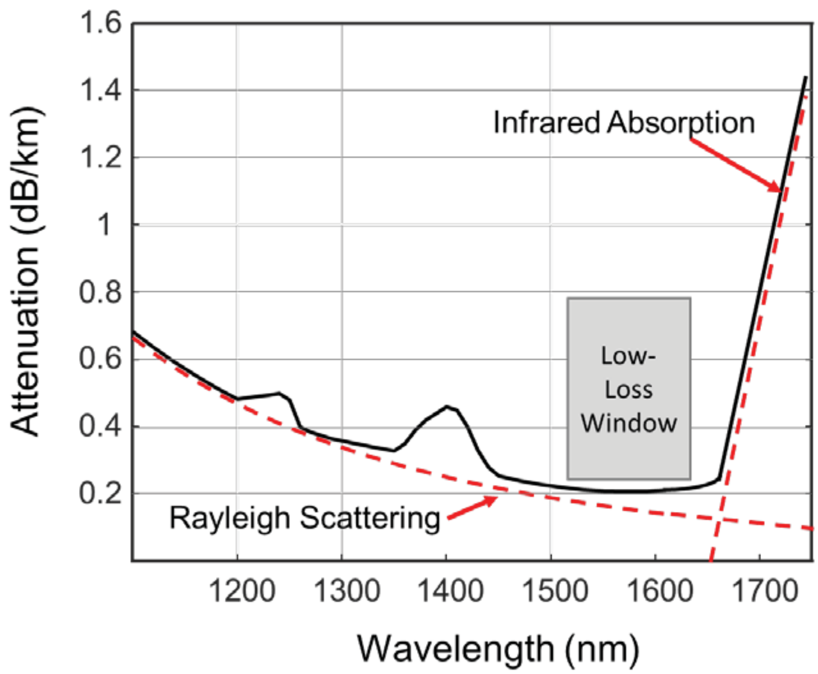


Figure 3: Optical Loss in Fiber versus Wavelength

Coaxial cables' loss is not flat for a given length versus frequency. Losses are dominated by two effects: conductor loss and dielectric loss. Conductor loss has a square root dependence on frequency, while dielectric loss is depends linearly on frequency. Figure 4 shows the loss of a fiber cable and coax cable versus frequency. Fiber cable of 1 kilometer length has a loss of 0.2 dB and is flat versus frequency. Coax cable of 10 meter length has flat loss which slowly rolls off to 10 dB at 10 GHz. Loss of the same type of coax with a length of 100 meters grows as the frequency increases. At 800 MHz, the loss is 20 dB, a 100 times lower than the initial power. Other advantages exist for fiber cables versus coax. Weight, cost, and thermal stability are some of them as well.

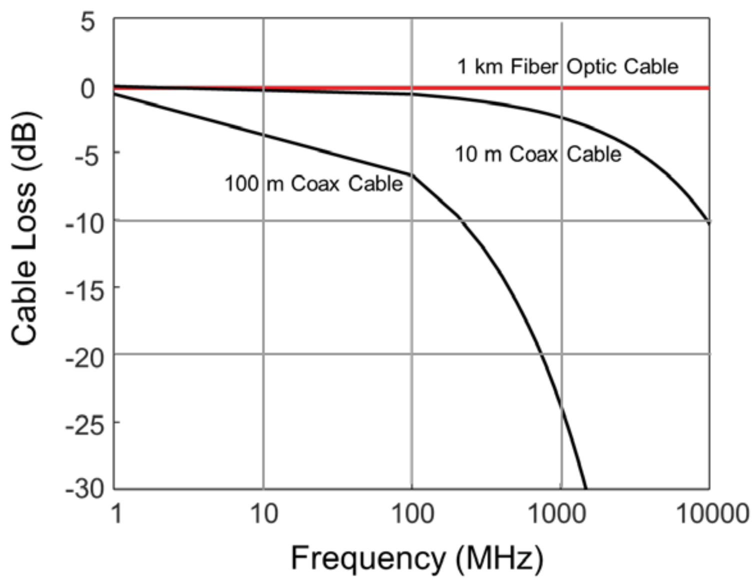


Figure 4: Loss of a Fiber Cable and Coax Cable versus Frequency

3.1 Analog vs. Digital

Digital and analog data metrics are different. Digital data uses discrete voltage levels for ones and zeros. Eye diagrams capture important metrics for digital data. Figure 5 shows an eye diagram for a practical data stream. Ones and zeros have a width which measures noise on the signal. Transitions between levels show non-instantaneous rise and fall times. Timing jitter increases the width of rise and fall transitions. The red eye mask measures the “openness” of the eye diagram. Bits within the eye mask are errors in the received data.

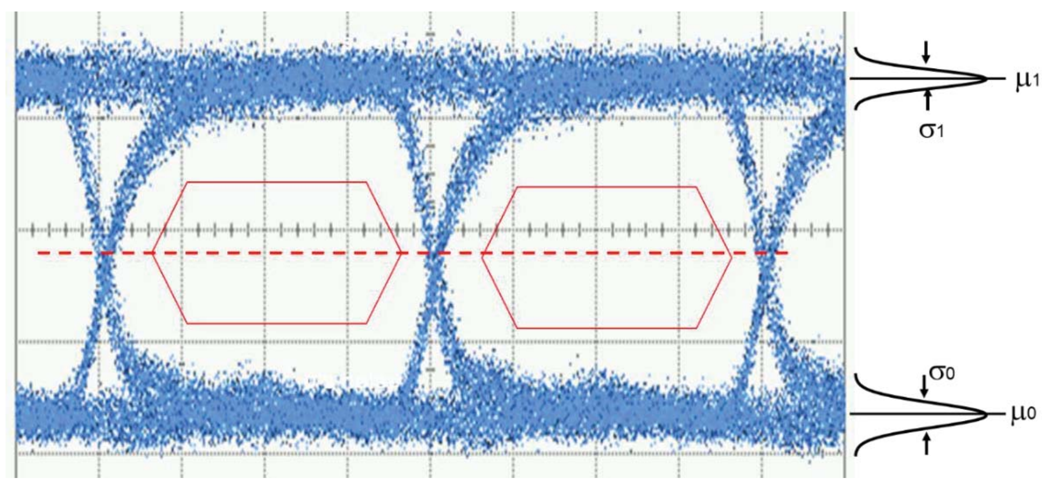


Figure 5: Eye Diagram for a Practical Digital Data Stream

Analog signal metrics are different from digital. Analog metrics are RF gain, RF noise figure, compression dynamic range (CDR) and spur free dynamic range (SFDR). Equivalent to the eye diagram, a plot of analog response captures the metrics. Figure 6 shows input RF power versus output power. The noise floor is related to the RF noise figure. The fundamental response

appears as a line with a slope of one. Taking the difference between the input and output powers is the RF gain. When the measured output power deviates from the ideal slope of one, compression occurs. When the output power is 1 dB less than the predicted power, the 1 dB compression point has been reached. The range of input powers where the signal is above the noise and below the 1 dB compression point is the CDR. The range of input powers, where the signal is above the noise but the spurious signal, represented by the IMD_3 line in Figure 6, is below the noise, is the SFDR.

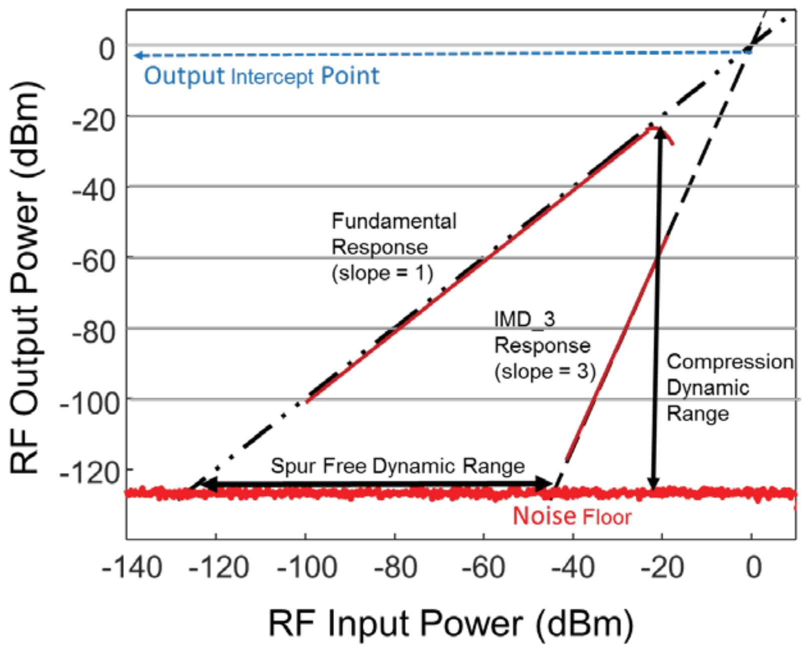


Figure 6: Input RF Power versus Output Power

3.2 RF Photonic Links

A RF link is a simple application to use RF photonics. Figure 7 shows an example of a RF photonic link connecting an antenna to a signal processing system.

A laser is connected to a photonic modulator. The RF signal is up-converted onto the laser light and sent down a fiber cable. A photodetector down-converts the RF signal to the electrical domain.

An RF photonic link should deliver an accurate replica of the RF signal. RF photonic links should be used for either long lengths or high frequency.

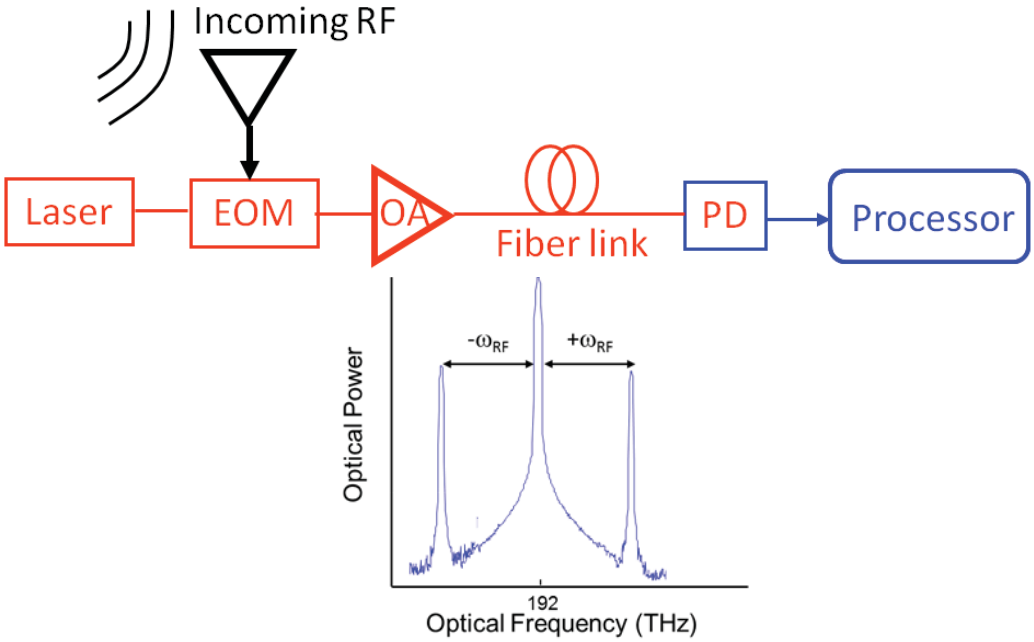
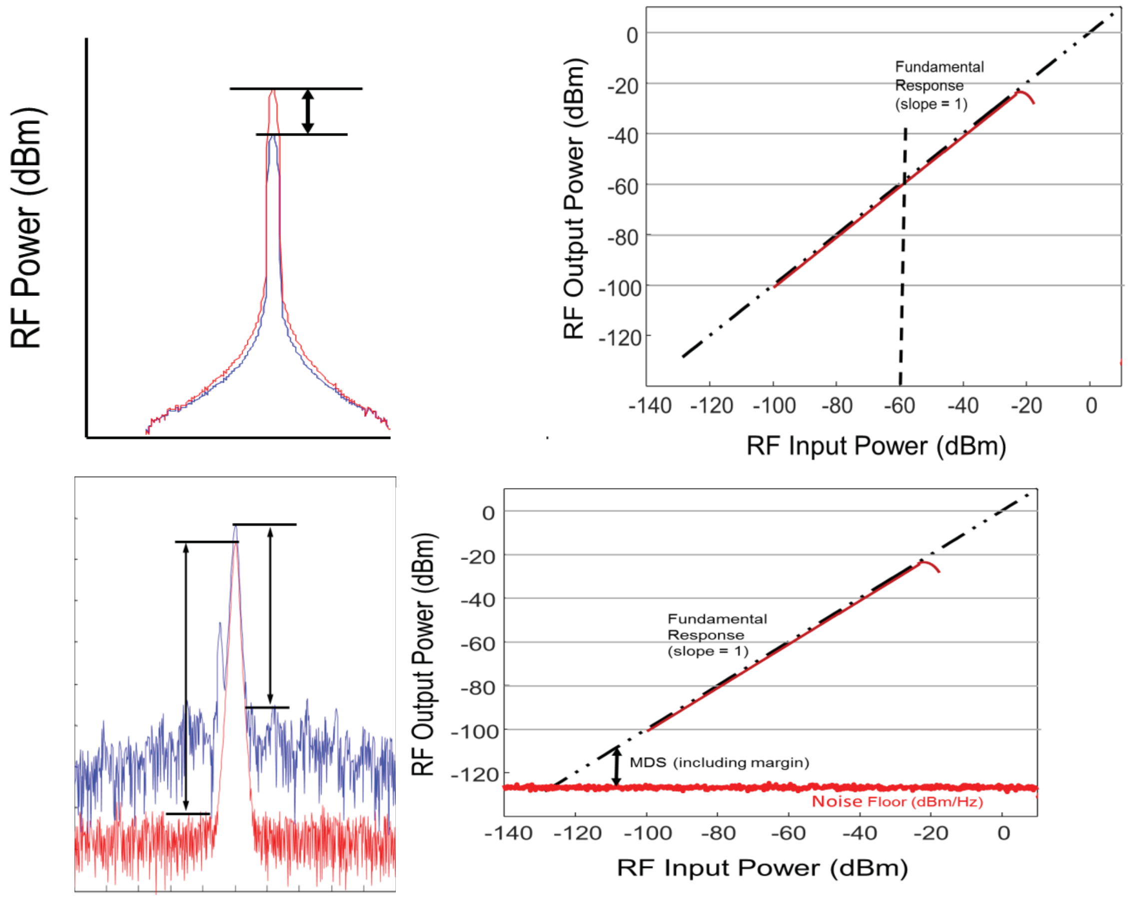


Figure 7: Example of RF Photonic Link Connecting an Antenna to a Processor

3.3 RF Metrics for Links

Four main RF metrics are RF gain, RF noise figure, SFDR, and CDR. RF gain is the ratio of the output RF power relative to the input RF power. RF noise figure is the change in the signal to noise ratio (SNR) at the input of the system relative to the SNR at the output. Figure 8 shows the measured RF gain and RF noise figure. The definition of minimum detectable signal (MDS) is also provided below.



$$MDS(dBm) = N_{th}(dBm) + NF_{RF}(dB) + 10\log_{10}(BW(Hz)) + Margin_{\min}(dB)$$

Figure 8: Measurements of RF Gain and RF Noise Figure along with Definition of MDS

The RF SFDR is range of input powers where the original input signal is over the noise floor while no spurious signals are. Spurious signal is a result of nonlinearities in the system.

Figure 9 shows different spurious signals generated from a nonlinear system. The system has two different single frequency tones input to it. The original two signals are observed, as well as several other spurious signals at the output.

Second and third harmonic spurious signals appear. Also intermodulation spurious signals appear as well. Second order intermodulations are at the sum and difference of the two input signals, while third order intermodulation spurious signals appear at the sum and difference of double one signal's frequency with the other signal's frequency.

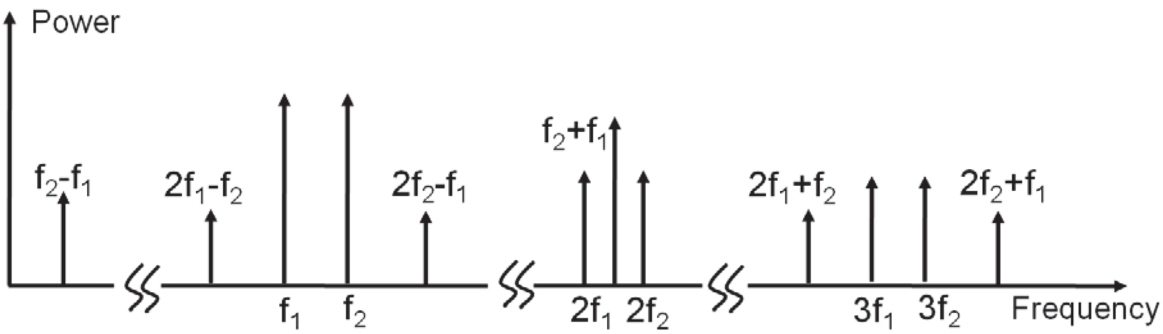


Figure 9: Different Spurious Signals Generated from a Nonlinear System

CDR is the range of input powers where the output signal is above the noise floor of the system and the output power follows the gain of the system. Figure 10 shows a CDR plot. The solid red line is the measured output power with the dashed black line as the ideal response line. The power is above the noise floor and follows the ideal response until it begins to roll off. When the measured output power is 1 dB below the ideal response, this input power is referred to as the 1 dB compression point.

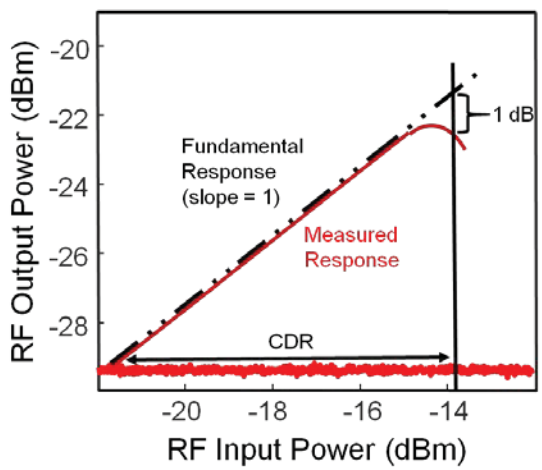


Figure 10: CDR Plot

3.4 Different Modulation Methods

Up-converting the RF signal into light can be done different ways. Direct modulation of the laser is one method. Another method is the use of an electro-absorption modulator (EAM). Both result in intensity modulation.

Phase modulators impart the analog signal onto the phase of the light. The signal is recovered after passing through an asymmetric interferometer (AMZ). A phase modulated link is shown below in Figure 11. After the AMZ, linewidth of the laser is converted to intensity noise. The added noise is shown in Figure 12.

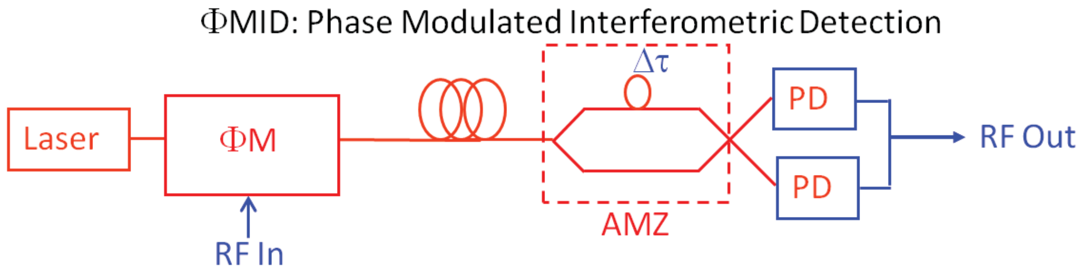


Figure 11: Phase Modulated Link with AMZ

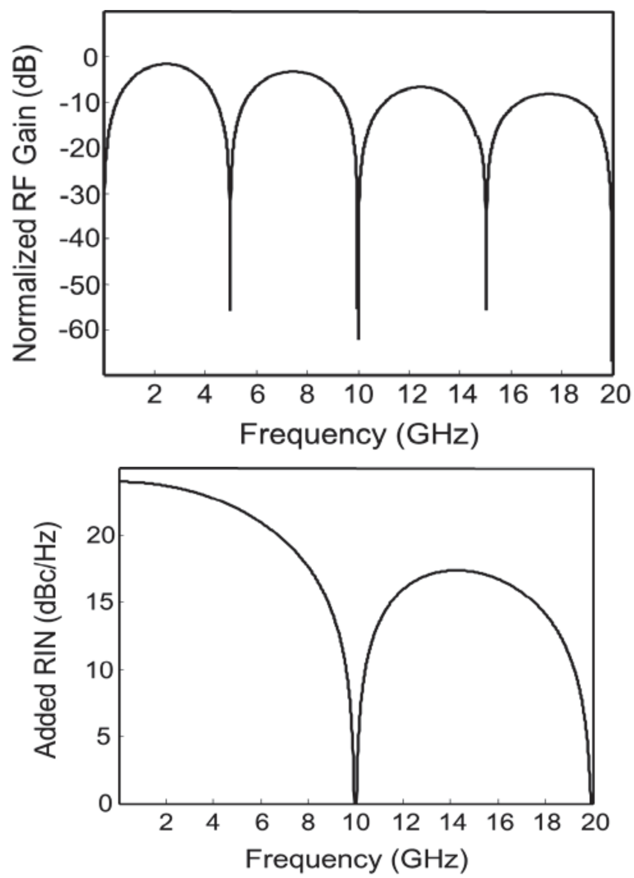


Figure 12: RF Response of the AMZ and Laser Linewidth Converted to Intensity Noise

Finally the Mach Zehnder interferometer based modulator (MZM) is used. The sinusoidal transfer function of the MZM appears above. In frequency, the output result is double-sideband modulation of the light.

This type of RF photonic link is referred to as an intensity modulated direct detection (IMDD) link (see Figure 13). Using an IMDD link, the RF gain is a function of V_{π} and the I_{dc}. Figure 14 shows RF gain versus DC photocurrent at different V_{π}. The higher the DC photocurrent, or the lower the V_{π}, the higher the RF gain.

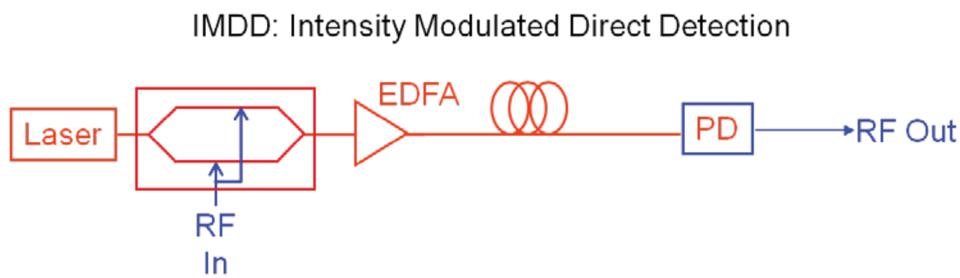


Figure 13: Intensity Modulated Direct Detection

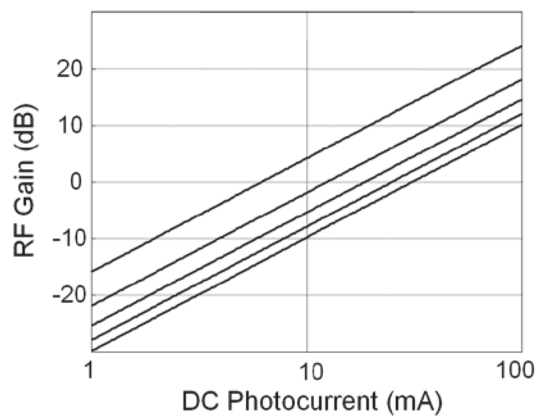


Figure 14: RF Gain versus DC Photocurrent at different V_π

3.5 Laser Performance

Laser provides the coherent light for the system. Two main factors describe the laser performance: output power and the relative intensity noise (RIN). Output power is directly related to the DC photocurrent, improving the RF gain and noise figure. Laser RIN sets a lower limit on the level of the noise floor in the system. Figure 15 shows measured RIN of two different lasers. Typical distributed feedback (DFB) lasers can have RIN levels in the range around -165 dBm/Hz.

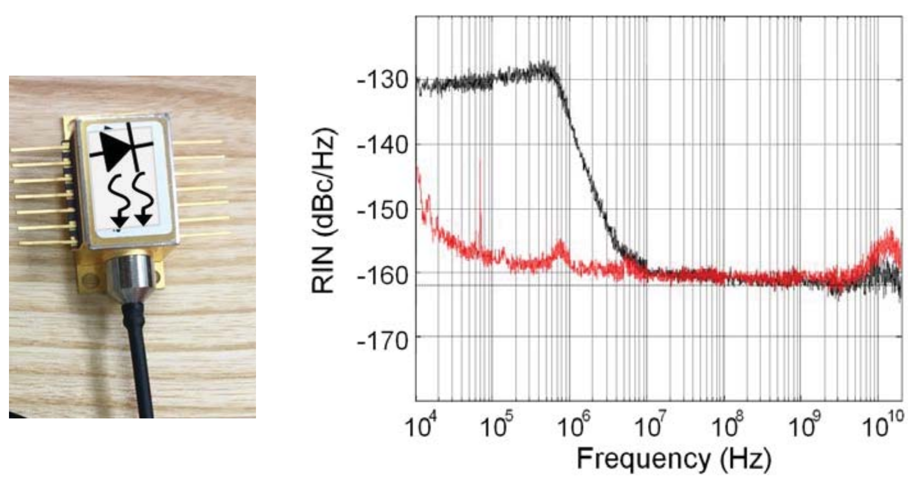


Figure 15: Measured RIN of Two different Lasers

3.6 Optical Amplifier Performance

Optical amplifiers are used to increase the optical power while keeping the RIN low. The increase in optical power can be large. However the amplifier will add additional noise.

Erbium-doped fiber amplifier (EDFA) is the most used amplifier and has noise penalties from 3-20 dB. Figure 16 shows an example of an EDFA and Figure 17 shows the impact of the noise penalty on RF Noise.

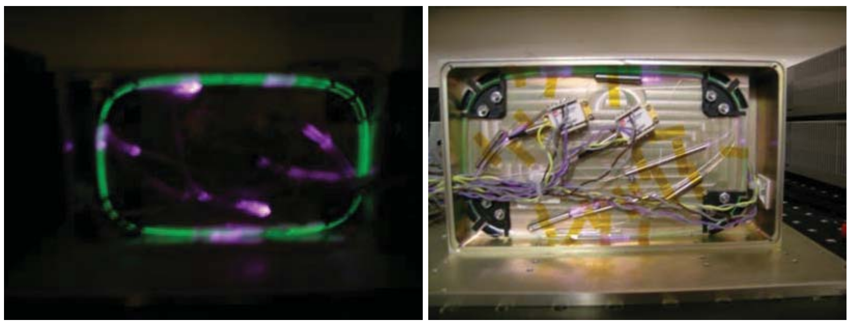


Figure 16: Example of an EDFA

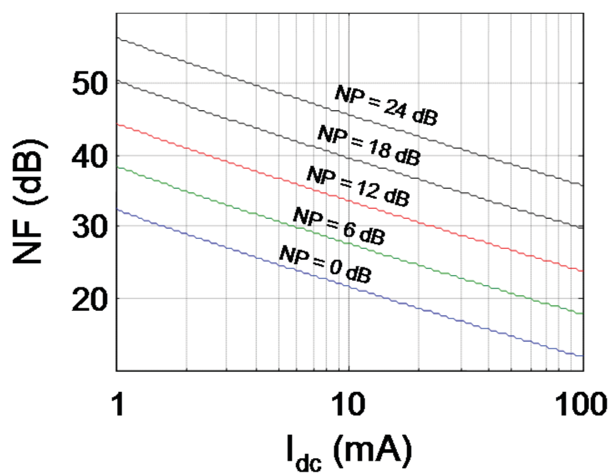


Figure 17: Impact of the Noise Penalty on RF Noise

3.7 Fiber Optic Power Handling Performance

The next photonic component is the optical fiber. The maximum input power the optical fiber can accept is important. After a specific amount of optical power, nonlinear optical effects begin. Beyond a certain power, the stimulated Brillouin scattering (SBS) effect occurs. When SBS occurs, reflected power increases exponentially versus input optical power (see Figure 18). Also output power does not increase but becomes constant and the SBS effect increases the added noise. Figure 19 shows the increased noise above the SBS threshold.

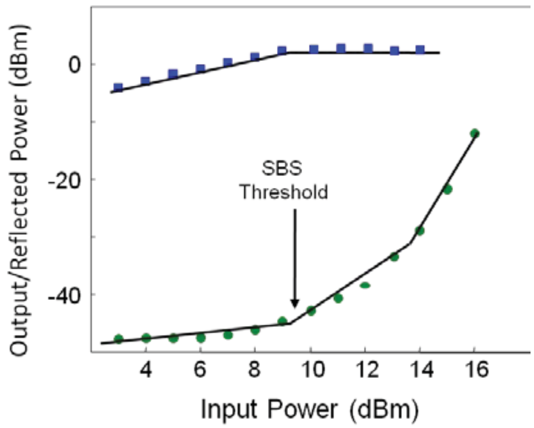


Figure 18: SBS Occurring, Reflected Power Increases Exponentially versus Input Optical Power

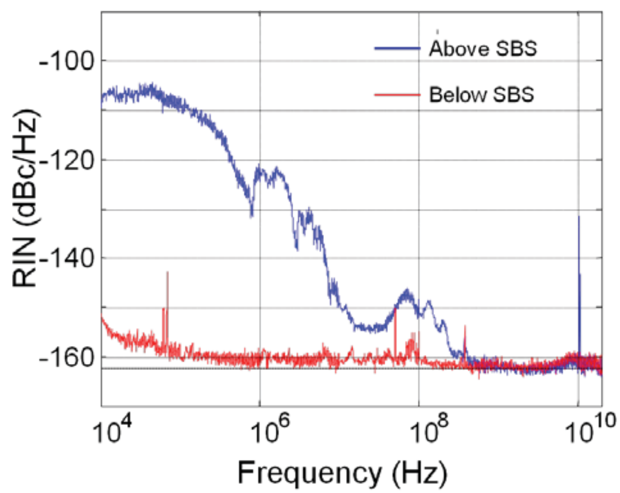


Figure 19: Increased Noise above the SBS Threshold

3.8 Fiber Optic Dispersion Performance

Fiber also has chromatic dispersion. For high RF frequencies, the optical sidebands will become out of phase with each other. This effect is known as "RF fading". The fading results are shown in Figure 20. The dispersion places a frequency limitation on the system.

Another effect is the increase in the even order distortion. The increase in the second harmonic power versus frequency appears in Figure 21. The second harmonic power grows very significant.

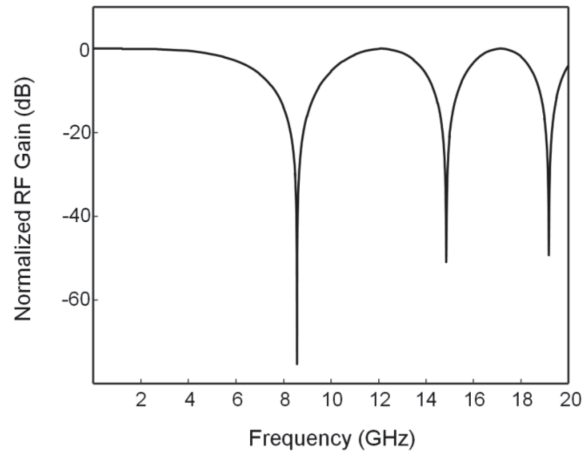


Figure 20: RF Fading Results

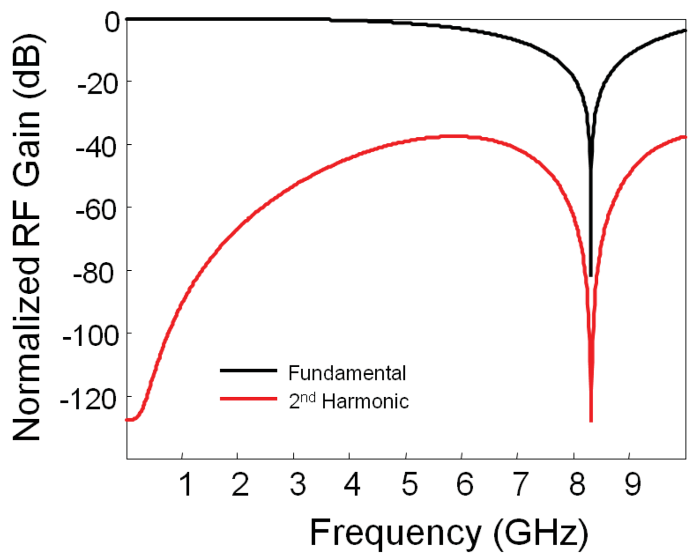


Figure 21: Increase in the Second Harmonic Power versus Frequency

3.9 Photodetector Performance

The last photonic component is the photodetector. The responsivity of the photodetector measures the photocurrent generated versus optical power input to the device. Higher responsivity generates more photocurrent. The responsivity is not completely linear. This leads to the photodetector adding spurious signals at the output. The optical power handling and the frequency response of photodetectors is also important. Power handling and the frequency response cannot be simultaneously improved. Figure 22 shows an example of a photodetector along with the responsivity curve and its nonlinear response.

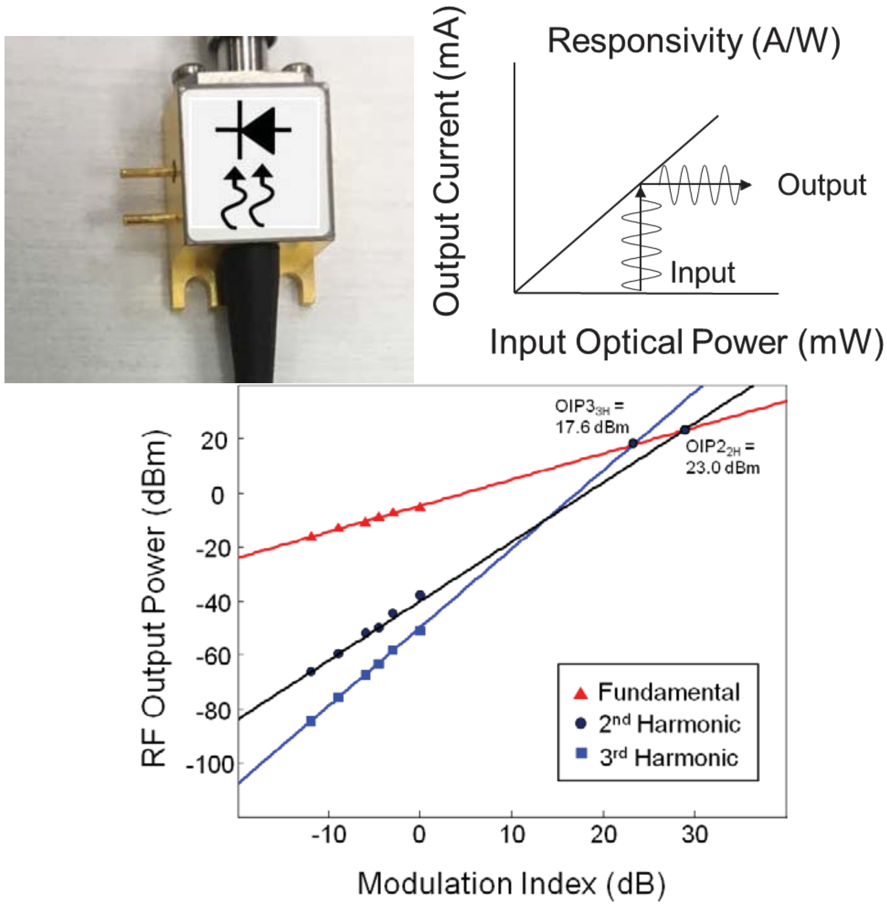


Figure 22:A Typical Photodetector along with its Responsivity and Nonlinear Performance

4. CONCLUSIONS

The analog delay line has an important purpose. An analog delay line is a good use for an RF photonic link. The external intensity modulation combined with direct detection link is the preferred option.

Different photonic components play a role in determining the performance of the system. Often they have limitations that have to be addressed in order to use the system as required.

LIST OF ABBREVIATIONS, ACRONYMS, AND SYMBOLS

ACRONYM	DESCRIPTION
AMZ	asymmetric interferometer
CDR	compression dynamic range
DC	direct current
DFB	distributed feedback
EAM	electro-absorption modulator
EDFA	erbium-doped fiber amplifier
IMDD	intensity modulated direct detection
MDS	minimum detectable signal
MZM	Mach Zehnder interferometer based modulator
RF	radio frequency
RIN	relative intensity noise
SBS	stimulated Brillouin scattering
SFDR	spur free dynamic range
SNR	signal to noise ratio